Inter-annual Variability and Prediction of Eddies in the Gulf of Aden and the Somali Current Region

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LONG-TERM GOALS

It is the research goal to understand and quantify the physical processes that determine the air-sea interaction, currents and hydrography in the western Indian Ocean and Arabian Sea, from diurnal time scales to inter-annual variability.

OBJECTIVES

The objective of this research is to provide a detailed investigation of the physical aspects of eddies found in the Gulf of Aden and in the Somali Current region in the Arabian Sea. The project aims to quantify the physical characteristics and statistics of the eddies, including their horizontal scales, their variation with depth, their influence on temperature, salinity and density, their generation and their life span.

More specifically, the objectives are

To provide a climatology and statistics of eddy fields in the Gulf of Aden based on observations from satellite altimeters and hindcast ocean models and to obtain a comprehensive understanding of the eddy generation and dynamics.

To investigate the impact of the eddies on air-sea interaction using correlation analysis between sea surface height anomalies and air-sea fluxes.

To determine the predictability of eddy fields from observations and numerical models.

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APPROACH

The questions above are being addressed primarily using two key sources of information. We proposed to analyze sea surface height from combined TOPEX/Poseidon, ERS and Jason altimeter data set and the output from state-of-the-art models to investigate the inter-annual variability of Gulf of Aden eddies and the mechanisms that generate them. SSH from T/P altimeter is the best source for high-resolution observations of the eddy fields. OGCM runs can be used for a detailed 3-D analysis of eddy dynamics and their impact on SST, upwelling and vertical density structure. Output with a 3-day frequency is available from the Ocean model For the Earth Simulator (OFES) hindcast run forced with NCEP re-analysis (1950 – 2005). This data is available to us at the International Pacific Research Center (IPRC) at University of Hawaii. Nowcast/forecast runs from the Naval Research Laboratory using HYCOM is available for selected periods from Jan 2003 until present from COAPS, FSU and will be included at a later stage of the project. Hindcast runs with and without data assimilation and forecast runs from the Naval Research Laboratory using HYCOM and NCOM are available for selected periods from Jan 2003 until present.

These data sources will be supplemented using observational data sets (Table 1 below) to determine an impact of eddies on air-sea interaction. In particular, it is anticipated that negative SST anomalies associated with cyclonic eddy activity may suppress mixing in the planetary boundary layer and weakening the surface wind as a result. Conversely, the relatively higher SST in anti-cyclonic eddies tend to increase the depth of the planetary boundary layer and locally increase the near surface wind speeds and the latent heat flux. AVHRR SST and QuikSCAT winds is used for this analysis.

For additional analysis and for evaluation of eddy predictability model output from eddy resolving layer models (NLOM) from the Naval Research Laboratory at Stennis Space Center will be used. The NRL NLOM have routinely been run in nowcast mode and forecast mode after assimilation of data and the output is available for analysis at the IPRC. Details are given in Table 2 below.

Observational Data Sets

Most available observational data sets are too limited in spatial and temporal resolution to adequately resolve eddies along the Arabian Peninsula. This is in particular true for air-sea heat flux data sets. The following data sets will be used for analysis:

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TABLE 1

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Observed Data set	Resolution	Time span	Variables
TOPEX/Poseidon/ERS/Jason1 combined altimeter data	0.25^o, weekly	10/92 - 6/03	SSHA
AVHRR Pathfinder v.5	4 km, daily	1985-2004	SST
WHOI OA heatflux	1.0^o, daily	1/81 -12/02	LH, SH
ISCCP	1.0^o, daily	1/81 -12/02	Net SW, net LW
QuikSCAT	0.25^o, 3 day	7/99-01/06	TX,TY
SeaWIFS	0.25^o, weekly	10/97-11/05	chlorophyll

These data sets have relatively high spatial and temporal resolution necessary to resolve the eddies. An exception is the ISCCP radiation data. This data has been interpolated to the same grid as the WHOI

objectively analyzed heat flux data from a resolution of 2.5^o. The latter data sets as well as Quickscat will be used to investigate possible air-sea interaction over eddies. The SeaWIFS data will only be used to help identify upwelling regions.

Monthly eddy climatology and inter-annual variability

The eddies drift westward along the Arabian coast so it is useful first to establish maps that show their monthly positions. Preliminary examination of high resolution model output from inter-annual runs indicates that several eddies appear in the same locations each year although year to year variability can be large. Therefore a monthly climatology will be established and year-to-year variations and climate extremes will be studied.

The manifestation of eddies is most significant in sea surface elevation so the first step is to produce maps of sea surface heights. Observed sea level heights will be computed from a combined weekly sea surface height anomaly (SSHA) from TOPEX Poseidon, ERS and Jason1 satellites. This data is mapped on a global irregular grid with 1/3° spacing on average. Data is available from October 1992 through December 2003. There is variability from year to year so maps of monthly variance will also be produced.

From the observed SSH fields the barotropic part of the geostrophic currents will be computed and compared with model results from OFES and HYCOM.

Other observed quantities with high resolution are difficult to obtain, in particular sub-surface quantities, so the project will rely on model simulations for variables other than SSH and SST. The following model data sets will be used:

Model	Resolution	Time of data	*Variables*
OFES 50yr run Climatology forcing	0.1^o , 54 levels	Last 8 years Daily output	*SSH, u,v,w,T,S (3d)*
OFES hindcast	0.1^o , 54 levels	Jan 1950 - Dec 2004 Monthly	*SSH, SST*
HYCOM nowcast	1/12°, 32 layers	Apr 2007 - present	*SSH,u,v,T,S (3d)*
HYCOM hindcast	1/12°, 32 layers	Nov 2003-Dec 2004	*SSH,u,v,T,S (3d)*
HYCOM simulation	1/12°, 32 layers	Jan 2003-Dec 2005	*SSH,u,v,T,S (3d)*
NLOM nowcast	1/32°, 6 layers	Apr 28, 2005 - now	*SSH, SST, u,v at surface*
NLOM nowcast	*1/16°, 6 layers*	*Jun 2002 -Mar 2006*	*SSH, SST, u,v at surface*

The Ocean Model for the Earth simulator is a full Ocean General Circulation Model and output from this model will be analyzed in most detail. The main advantage of the NRL NLOM model output is the higher horizontal resolution which may give different eddy characteristics and statistics than OFES or T/P SSH. In that case there is a possibility that the resolution of the observed SSH is inadequate.

Eddy Characteristics

The eddy scales will be determined from the data and models above. This includes eddy diameter, current speed, propagation speed and variation with depth.

The associated changes in temperature, salinity and density will be computed for a large number of eddies. Correlation of eddy scales between observations (SSH and derived barotropic geostrophic velocities) and model variables will be computed.

Generation mechanisms

The main hypothesis is that the eddies along the southern shore of the Arabian Peninsula primarily are generated by remotely forced Rossby waves. Along the west coast of India the wind generates upwelling and downwelling patterns, which result in Rossby wave radiation across the Arabian Sea (Jensen, 1991). This Rossby wave radiation was later confirmed by SSH observations from Topex/Poseidon (Brandt et al, 2002). A competing mechanism during the southwest monsoon is an extension of the Somali Current through the gap between the island of Socotra and the Horn of Africa which may drive eddy flow in the entrance to the Gulf of Aden.

Prediction

The remote forcing leads to a potential for forecasting the eddy field. It is proposed to produce correlation maps between SSH anomalies for a number of locations near 65^oE with latitudes ranging from 10^oN to 22^oN using the T/P-ERS data set. The same calculation will be computed for the OFES and NRL models. A comparison between the NRL nowcast model and the NRL forecast model output will reveal if successful forecasting of eddies can be done with an operational model.

WORK COMPLETED

In this section, representative results obtained since the last report are discussed.

Eddies in the Gulf of Aden during February-March

Bowers et al., (2002) reported two cyclonic eddies and an anti-cyclonic eddy from observations in February 2001. One question we addressed is if that scenario represents a typical late winter condition. We used the output the OGCMs and found the strongest eddy activity in the Gulf of Aden during February and March.

As a first step we extended our calculation of monthly absolute SSH from TOPEX/Poseidon/JASON to cover the time span from 1993 to 2007. It appears that the northeast monsoon season 2000-2001 is fairly typical. Using 7-day composites of SSH from T/P, we examined eddies in the Gulf of Aden during February and March in the 15 years covered by our analysis. Figure 1 below show the SSH and the associated geostrophic currents for 2001 through 2004 for these two months. The two first years have similar circulations and do represent a more common circulation pattern, while cyclonic eddies are absent during February- March 2003. In contrast, a total of 3 cyclonic eddies are present during the same months in 2004. On average during the 15 years from 1993 to 2007, we find an average occurrence of 1.40 for cyclonic eddies and an average 1.64 for anti-cyclonic eddies for February and

March. Table 1 gives the number of eddies for each of those months during the years investigated. Only persistent eddies with a fully closed circulation were included in the count.

We find the anti-cyclonic eddies are more prevalent and tends to be more energetic and have a longer lifespan than cyclonic eddies. The T/P SSH fields support this result (Fig 1), but our conclusion is corroborated using output from the oceans models.
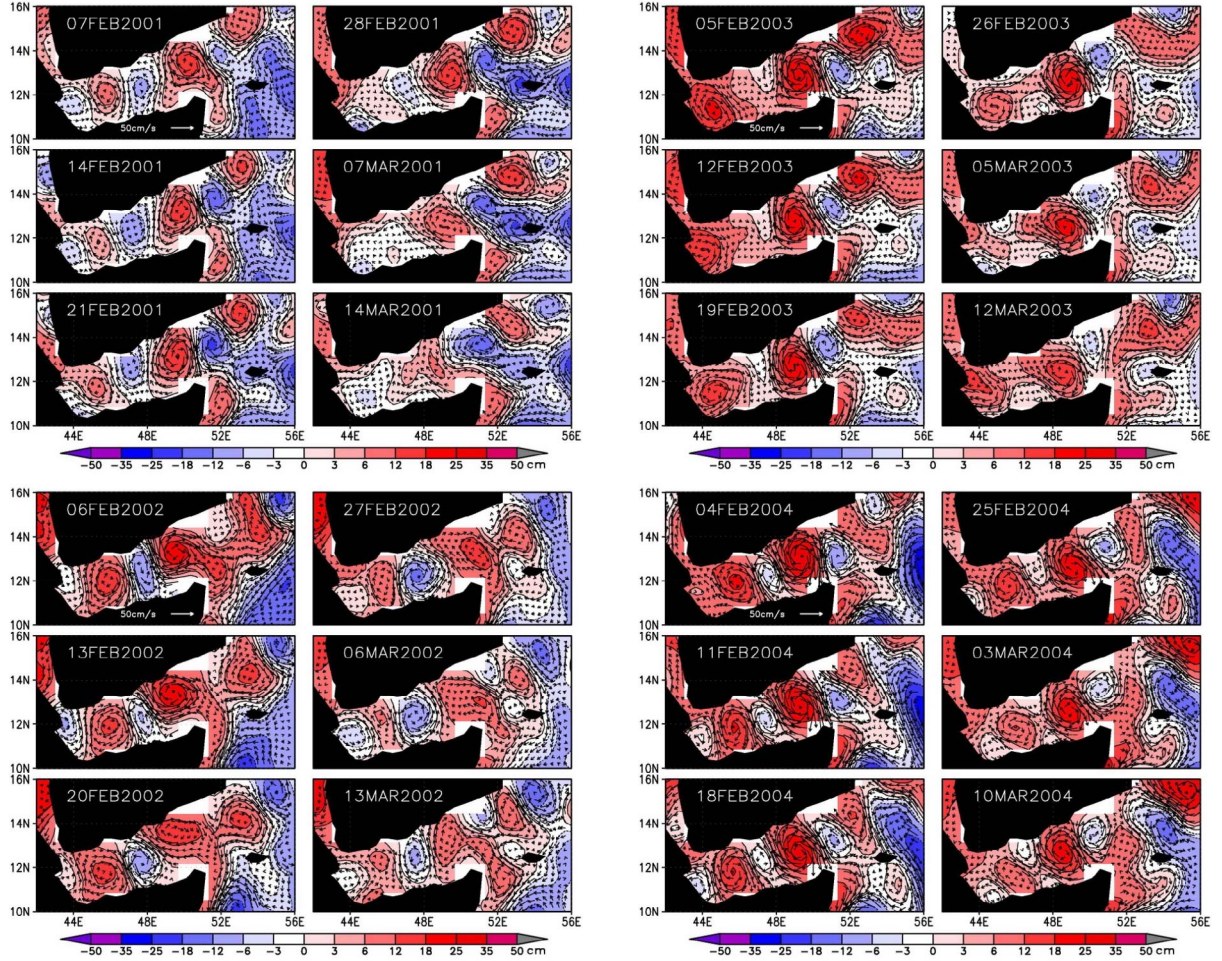
Figure 1. Absolute Sea Surface Height (SSH) and calculated geostrophic currents from TOPEX/Poseidon in February-March for 2001 to 2004.

The flow in February 2001 (Fig.1) shows a common situation with a cyclonic eddy north-east of Socotra with strong anti-cyclonic eddies on each side. The southward flow on the western side of the cyclonic eddy is intense and connected to the Somali Current with a continuous southward flow through the strait between the continent and Socotra. Although the year to year variability is high, there is a tendency for the southward flow to be near the African continent in February and close to the coast of Socotra in March.

During summer the eddy activity in the Gulf of Aden is much less pronounced than during winter, while the opposite is true for the Somali Current region in general. The eddy activity for the entire region peaks in September as shown in last year's report. The most intense eddy found in the Gulf of Aden was an anti-cyclonic eddy spanning the gulf from the Arabian coast to just south of Socotra and from 49°E to 53°E in September 1997. During that year, which is an El Nino year as well as an Indian Ocean Dipole year, the summer Somali Current was particularly intense (e.g. Jensen, 2007).

TABLE 1 Number of closed eddy circulations in the Gulf of Aden

| YEAR	FEBRUARY		MARCH	
	Cyclonic	Anti-cyclonic	Cyclonic	Anti-cyclonic
1993	2	2	2	2
1994	1	1	0	1
1995	1	0	2	0
1996	0	1	1	2
1997	1	2	1	2
1998	2	2	2	2
1999	1	1	0	1
2000	2	2	2	2
2001	2	2	1	1
2002	2	2	2	2
2003	0	2	0	2
2004	3	2	3	2
2005	2	2	2	1
2006	2	2	2	2
2007	1	2	0	2
Average	1.47	1.67	1.33	1.60

Ocean General Circulation Models

We have also examined output from general circulation models. Last years report showed a comparison between monthly mean TOPEX/POSEIDON sea surface height compared to an OFES model run using NCEP forcing. We have done further comparisons with an OFES run using QuikSCAT wind stress and for the global 1/8°NCOM, which includes assimilation of TOPEX/POSEIDON. For a free run (without data assimilation) , we have investigated the 1/12° resolution global HYCOM from the US Navy nowcast/prediction system (e.g. Hurlburt et al, 2008) for the region of interest (Fig. 2).

 HYCOM simulations is showing vigorous eddy activity in the Somali region and confirms our original hypothesis that that two generation mechanisms exist: 1) Anti-cyclonic eddies tends to be generated by incoming Rossby waves from the east impinging on the Arabian peninsula. This seems to be the dominant generation mechanism. 2) Cyclonic eddies may be formed by throughflow between the Horn of Africa and the island of Socotra during the summer monsoon. However, there is interaction between the eddies in the Gulf of Aden and in the Somali Current region as discussed above.

GLOBAL 1/12º HYCOM SSH on February 14
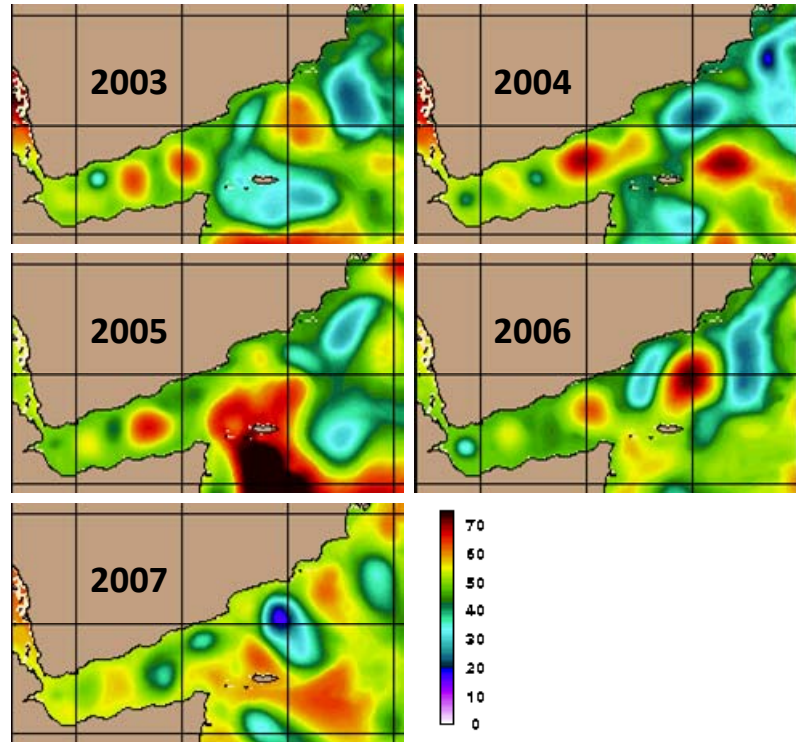
Figure 2. Sea Surface Height from 2003-2007 from a HYCOM simulation forced by daily winds and buoyancy fluxes. Fields from February 14 for each year is shown.

Vertical structure of eddies

A surprising observation by Bower et al.(2002) was that the eddy motion was found to depths exceeding 1000 m with currents speeds at about 0.1 m/s. At 500 m velocities up to 0.3 m/s were observed. We examined the Gulf of Aden eddies from model simulations from OFES, the Global 1/8º NCOM and the 1/12º HYCOM. All models have eddies which have a smaller velocity signal at depth than the observations by Bower et al. (2002). The motion is mainly confined to the upper ocean above the main thermocline, which is found near 200 m. Eddies from global NCOM shown in Fig 3 is a typical example of the eddies found in the OCGMs. At 700 m we find velocities of 0.1 m/s in Global NCOM. In OFES we have velocities up to 0.2 m/s at 600 m.
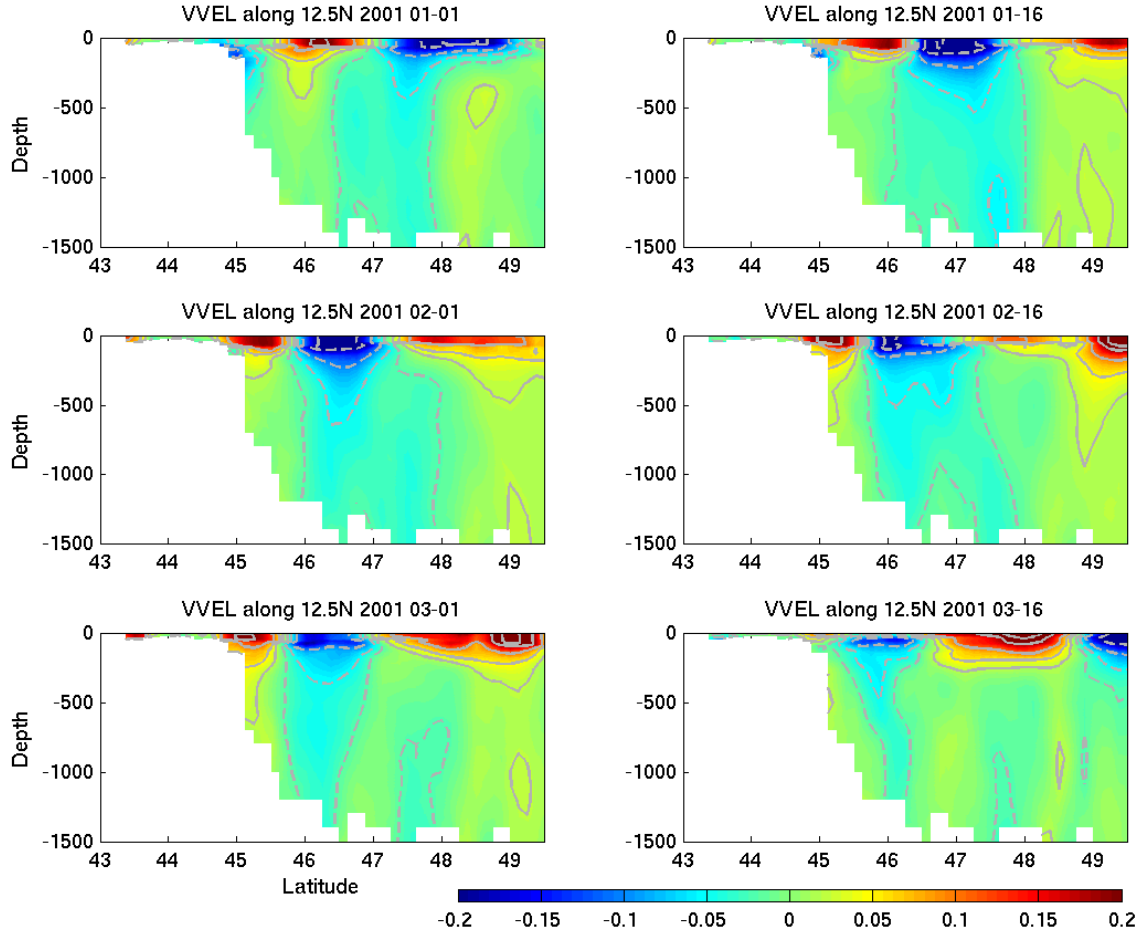
Figure 3. Vertical sections of meridional velocity through the Gulf of Aden on Jan 1, 2001. Northward velocity is enclosed by solid lines and southward velocity components by broken lines. The minimum contour level is 0.02 m/s, followed by 0.05 m/s and 0. 1 m/s. For larger velocities the contour interval is 0.1 m/s.

Generation mechanisms experiments

The three global model above (OFES, HYCOM and NCOM) are not practical models to use for numerical experimentation due to the computational resources required. We have used a high resolution (0.1°) 6.5 layer model that includes prognostic temperature and salinities (Zuojun Yu, personal communication). The model simulates the eddies in the Gulf of Aden as realistic as the OGCMs for the upper ocean, although by its design, prevents the eddies from reaching near as deep. The insert to the right in Fig 4 show a schematic of the eddy observations by Bower et at.,(2002).
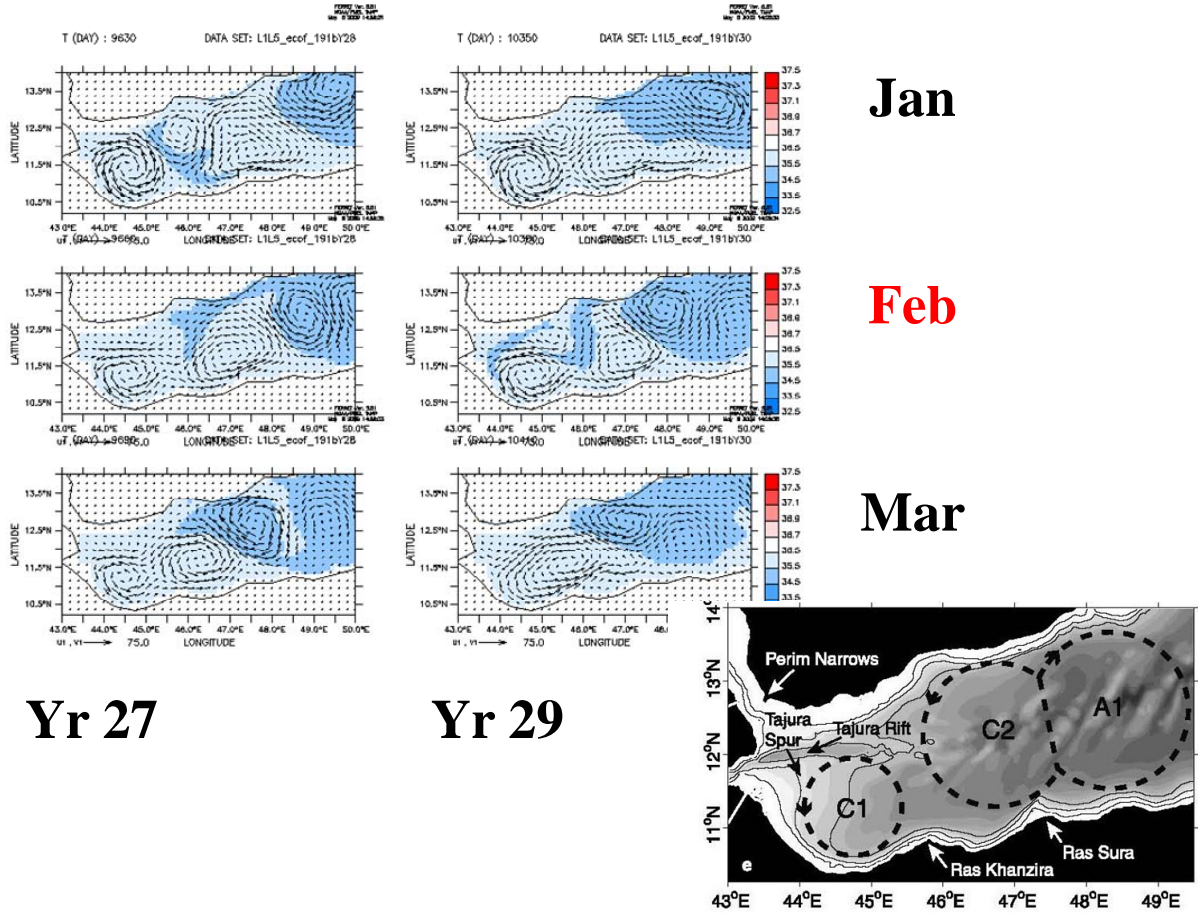
Figure 4. Upper ocean currents from a 5 ½ layer ocean model forced with monthly mean climatology winds is able to reproduce the observed eddies in the Gulf of Aden as observed by Bowers et al. (2002). The insert show the interpretation of the eddy field observed in February, 2001.

As seen the layer model simulates the eddies in overall agreement with the observations with respect to the sign of rotation and the location of the eddies. The layer model was used for a number of sensitivity experiments to determine the forcing of the eddies.

One experiment closed the gab between the continent of Africa and Socotra. This decreased the number of eddies in the Gulf of Aden compared to our control run, confirming the generation mechanism by flow through the channel as suggested by our OGCM analysis.

A second experiment demonstrated that the outflow of Red Sea Water intensified the cyclonic eddy in the western end of the Gulf of Aden. This result is unexpected. There was also an impact on the eddies further east, but it is more likely due to eddy-eddy interaction than direct forcing by the outflow from the Red Sea.

A third experiment used monthly climatological winds from different wind products (COADS, QuikSCAT (200-2007), ECMWF (1998-2003) and ECMWF(1992-1998). The number of eddies and their general position was independent of the forcing, but there were fairly large variations in eddy

intensity and life time. The simulation using COADS forcing was showing a larger variability than those forced with other wind climatologies.

Products

Jensen, T. G.: Evolution of the Somali Current during La Nina, El Nino and Indian Ocean Dipole years. Manuscript in progress.

Jensen, T.G, Z. Yu and J. P. McCreary: Eddies in the Gulf of Aden – an overview. Manuscript in preparation.

Jensen, T. G., (2008): Variability of the Somali Current System. Topex/Poseidon and OFES results. Powerpoint presentation.

Yu, Z., T. G. Jensen, A. Ishida, R. Furue and J. P. McCreary (2009): Mesoscale Eddies in the Gulf of Aden. Powerpoint presentation

IMPACT/APPLICATIONS

The Gulf of Aden is important for the world economy. It is one of the most active shipping lanes in the world, connecting the Indian Ocean to the Suez Canal. Over 22,000 ships pass through the Gulf annually.Nearly 3 million barrels of oil are transported through the Gulf of Aden daily. In addition, Yemen currently exports 350 to 370,000 barrels per day of crude oil through the terminals at Ras Isa and Ash Shihr. To the south near the island of Socotra and near the Somali coast shipping is exposed to attacks from pirates at an increasingly alarming rate. In 2007 there were 13 attacks. In 2008 over 300 ships were attacked of which 40 vessels were hijacked, including a Saudi supertanker carrying $100 million worth of crude oil. Given the strategic and economic importance of the Gulf of Aden, the entrance to the Red Sea and hence the Suez Canal, surprisingly little attention has been given to the strong eddy activity found in the area. For instance, the otherwise comprehensive review of the physical oceanography of the Indian Ocean by Schott and McCreary (2001) does not have a single reference to studies about eddies along the south shore of the Arabian Peninsula. It is expected that a better knowledge of the currents, in particular the seasonal changes of the energetic meso-scale eddies in Gulf of Aden, will be useful for naval ship operations, search and rescue and control of oil spills in this important geographic area.

RELATED PROJECTS

There are no related projects.

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